AFRL-HE-AZ-TR-2004-0078

United States Air Force Research Laboratory

EVALUATING THE SPATIAL RESOLUTION OF FLIGHT-SIMULATOR VISUAL DISPLAYS

George A. Geri

Link Simulation and Training
6030 South Kent Street
Mesa, Arizona 85212-6061

Marc D. Winterbottom
Byron J. Pierce

Air Force Research Laboratory
6030 South Kent Street
Mesa, Arizona 85212-6030

June 2004

Approved for public release; distribution is unlimited

Human Effectiveness Directorate
Warfighter Training Research Division
6030 South Kent Street
Mesa, AZ 85212-6061

NOTICES

BYRON PIERCE
Project Scientist

HERBERT H. BELL
Technical Advisor

CURTIS J. PAPKE, Colonel, USAF
Chief, Warfighter Training Research Division

Contract Number: F41624-97-D-5000
Contractor: Link Simulation and Training

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2004	Final	March 2003 to March 2004

4. TITLE AND SUBTITLE
Evaluating the Spatial Resolution of Flight-Simulator Visual Displays

5a. CONTRACT NUMBER
F41624-97-D-5000

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
George A. Geri
Marc D. Winterbottom
Byron J. Pierce

5d. PROJECT NUMBER
1123

5e. TASK NUMBER
B1

5f. WORK UNIT NUMBER
23

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Link Simulation and Training
6030 South Kent Street
Mesa, AZ 85212-6061

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Training Research Division
6030 South Kent Street
Mesa AZ 85212-6061

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL; AFRL/HEA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-HE-AZ-TR-2004-0078

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Air Force Research Laboratory Technical Monitor: AFRL/HEAS, Dr. Byron Pierce, DSN: 474-6219, COMM: (480) 988-6561 Ext. 219

14. ABSTRACT
This paper documents a technique for assessing the spatial resolution of visual display systems like those currently used for flight simulation at the Air Force Research Laboratory (AFRL), Mesa, Arizona. The introduction defines spatial resolution, and how best to apply the concept in the context of visual display evaluation. The measurement technique is described in detail, as are the CCD-based light measurement device and the techniques developed to calibrate it. Typical spatial resolution data are presented for a variety of display systems. The various steps required for data analysis, and suggested methods for implementing these steps using standard applications programs are presented. The computer programs used to generate and display the test patterns and to estimate spatial resolution are described and are available from Defense Technical Information Center (DTIC).

15. SUBJECT TERMS
Spatial Resolution, Visual Display Resolution, Visual Performance, Aircraft Aspect Angle Recognition, Training Effectiveness

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Mr. Don Beedle
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED	41	480.988.6561 x-552 DSN 474-6552

ABSTRACT

This paper documents a technique for assessing the spatial resolution of visual display systems like those currently used for flight simulation at the Air Force Research Laboratory (AFRL), Mesa, Arizona. The introduction defines spatial resolution, and how best to apply the concept in the context of visual display evaluation. The measurement technique is described in detail, as are the CCD-based light measurement device and the techniques developed to calibrate it. Typical spatial resolution data are presented for a variety of display systems. The various steps required for data analysis, and suggested methods for implementing these steps using standard applications programs are presented. The computer programs used to generate and display the test patterns and to estimate spatial resolution are described and are available from Defense Technical Information Center (DTIC).

TABLE OF CONTENTS

LIST OF FIGURES vi

LIST OF TABLES vi

PREFACE vii

ACKNOWLEDGEMENTS vii

1. Introduction 1

2. Spatial Resolution and the Modulation of Periodic Patterns 2

3. Proposed Technique for Estimating Display Spatial Resolution 3

- 3.1 Measurement Procedure 4
  - 3.1.1 Black level, maximum luminance, and luminance fall-off 4
  - 3.1.2 Initial display brightness and contrast adjustments 5
  - 3.1.3 Gamma correction and luminance calibration 6
  - 3.1.4 Display spatial resolution measurements 7
- 3.2 Typical Spatial-Resolution Measurements 10
- 3.3 The Control of Relevant Display System Parameters 12
- 3.4 Limitations of the Proposed Technique 13
- 3.5 Modulation Transfer Function (MTF) Analysis 13

4. Conclusions 14

5. REFERENCES 16

6. APPENDIX A 17

SELECTING A CCD CAMERA AND LENS 17

- 6.1 Number of Pixels 17
- 6.2 Field of view 17
- 6.3 Binning 18

7. APPENDIX B 19

CCD-CAMERA CALIBRATION 19

- 7.1 Measurement consistency 23
- 7.2 Conversion of CCD Output to Luminance 19
- 7.3 Exposure duration and binning 20

7.4 Flat-field correction 21
7.5 Photopic Correction 22

8. APPENDIX C 25
DATA ANALYSIS WORKSHEETS IN MICROSOFT® EXCEL....................................25
8.1 Luminance Calibration (LC) Workbook..25
8.2 Visual Display Evaluation (VDE) Workbook 26

9. APPENDIX D..29
ACRONYMS AND DEFINITIONS 29

10. APPENDIX E 30
FILES ON CDROM 30

11. APPENDIX F..31
EQUIPMENT USED..31

LIST OF FIGURES

Figure 1 Grille Pattern Used for Measuring Spatial Resolution. 3
Figure 2 Checkerboard test pattern used for display adjustment. 5
Figure 3 Contrast series test pattern for display adjustment. 5
Figure 4 Example gamma function for a CRT display. 7
Figure 5 Example grille patterns (left) and luminance measurements (right). 9
Figure 6 Measured contrast modulation for various grille line widths on a CRT display. 10
Figure 7 Two methods for assessing spatial resolution. 14
Figure 8 Conversion of CCD output to luminance values. 19
Figure 9 Effect of luminance and exposure duration on CCD output. 20
Figure 10 Effect of CCD binning and exposure duration on CCD output. 21
Figure 11 CCD calibration with an integrating sphere. 22
Figure 12 Comparison of CCD response and the CIE photopic luminosity function. 23
Figure 13 CCD pixel values measured for on two successive days. 24

LIST OF TABLES

Table 1 Spatial Resolution Data for Various Displays. 11

PREFACE

The research was conducted at the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HEA), Warfighter Training Research Division in Mesa, Arizona. This research is documented under Work Unit 1123-AE-01, Warfighter Training Research Support, under contract F41624-97-D-5000 to Link Simulation and Training, a division of L-3 Communications Corp. The Laboratory Task Monitor was Dr. B. Pierce, and the Laboratory Contract Monitor was J. Carroll.

ACKNOWLEDGEMENTS

We would like to thank Bill Morgan for developing the Visual Basic code used to generate the display test patterns which have been included on a compact disc with this Technical Report. We would also like to thank VDC Display Systems and Barco for providing the video display demonstration units which in many cases were used for this research.

EVALUATING THE SPATIAL RESOLUTION OF FLIGHT-SIMULATOR VISUAL DISPLAYS

1. Introduction

Spatial resolution is one of the most fundamental characteristics of a visual display. It is also one of the most commonly misused terms in the area of display design and evaluation. One reason for this misusage is that the spatial resolution of display devices is of great practical importance and must therefore be conveyed to a very diverse group of end users. An example of this is the almost universal practice of specifying resolution by the *pixel format* (i.e., the number of horizontal and vertical pixels in a visual display). The pixel format is obviously related to resolution, it is easy to specify and interpret, and it has a clear physical meaning. However, if a display device, such as a cathode ray tube (CRT) projection display, is not optically focused, its resolution can be reduced, even though the number of pixels addressed by the graphics hardware and CRT electronics has not changed.

The use of the term visual acuity (and specifically Snellen acuity) as a synonym for resolution is another example of how a familiar term can come into common and inappropriate usage. Most people have heard and used the term "20/20 vision" as a synonym for "good vision". This colloquial usage invites the following assumptions: 1) identifying the appropriate letters on a Snellen chart implies good vision, 2) the ability to discriminate the gaps in those letters determines whether they can be identified, and 3) the size of the gap is "x" minutes of arc, and therefore discriminating "x" minutes of arc is equivalent to "good vision". Every one of these assumptions is plausible, and every one, like many others that could be listed here, is inaccurate (Ginsburg, 1994; Rubin & Walls, 1969). Further, not only is the fundamental concept wrong, but the use of a number such as 20/20 can falsely imply quantitative attributes that are in themselves misleading. For instance, it is often implicitly assumed that if 20/20 is "good vision", then 20/10 must somehow be "super vision", or that 20/40 vision is half as good as 20/20 vision. Again, such interpretations can be misleading.

In addition to identifying and assessing the needs and capabilities of the end user, another major consideration in determining the most appropriate measure of spatial resolution is how the data will be used. In order to convey the quality of a display to a physicist, for instance, it may be appropriate to specify a modulation transfer function (MTF). This method of assessing display spatial resolution is described in detail by Kelly (1992). While MTFs convey a great deal of information, and the MTF approach is very powerful, unless extensive quantitative detail is provided, the results can easily be misinterpreted. In addition, the quantitative nature of the MTF approach is very appealing, and too often the mere quoting of "bandwidths" or "cut-off frequencies", is substituted for a discussion of the system characteristics actually relevant to the particular application. For instance, knowing that the bandwidth of a display system is 0.3 cycles per mm may be of little use in determining whether a displayed ground target would be visible (much less identifiable) to a pilot in a flight simulator. It obviously cannot hurt to have this information but it may not be necessary and it may not adequately describe the capabilities of the display system.

First, briefly discussed is how to define the term resolution. Then, the proposed measurement technique, which is believed to provide a meaningful specification of spatial resolution in the context of visual displays, and particularly those used for flight simulation and visual display research is presented. Finally, preliminary results of applying the proposed technique to the evaluation of several visual displays are summerized. The technique proposed here necessarily represents a compromise among analytical rigor and reasonable ease of measurement. However, the results are easily interpretable and should be of practical use to end-users of diverse interest and experience.

2. Spatial Resolution and the Modulation of Periodic Patterns

One major problem in specifying the spatial properties of a visual display is that the term spatial resolution is often neither well-defined nor well-understood by those who use it. Webster’s dictionary defines resolution as: *the process or capability of making distinguishable the individual parts of an object, closely adjacent optical images, or sources of light.* The spatial resolution of a visual display, therefore, may be thought of as the capability of the system to display very fine details at a contrast level high enough to be readily distinguishable by an observer. A high-resolution display should be able to display two adjacent thin lines such that they are distinguishable from one another at some specified and relevant criterion level.

The square-wave function shown in Figure 1(a) represents an idealized luminance distribution that corresponds, in the case of a display system, to the pixel values in the video memory of the image generator (IG). Note that a square-wave has an infinitely rapid transition from one luminance level to another, and so cannot be realized by any physical system. In order to display the luminance values represented by the square wave, those values must be interpreted by at least four components in a CRT-based display:

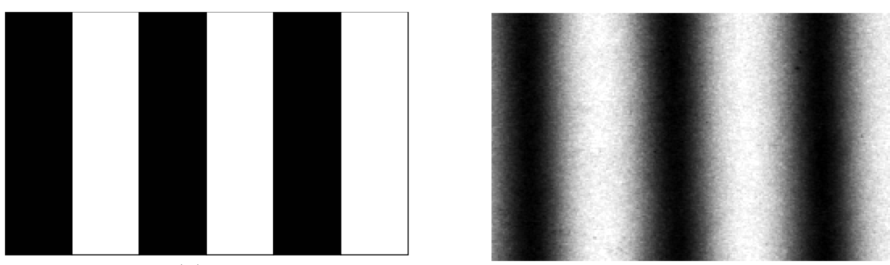
1) the digital-to-analog converter (DAC) of the video card

2) the electronics that drive the CRT beam

3) the CRT phosphor and

4) the effective imaging system represented by the CRT lens and the display screen.

Each one of these components has a limited bandwidth (i.e., capability to pass on spatial frequencies to the next device in the chain). As a result, more of the higher spatial frequencies that correspond to sharp edges (such as those making up the square-wave in Figure 1(a)) are removed at each stage. In other words, the display system is effectively a low-pass filter. The result of this filtering is shown in Figure 1(b), which is an image of the square-wave pattern as it actually appears on the display screen. The blurring associated with the reduction of the higher spatial frequency content of the input square wave is evident.



(a) (b)

Figure 1 Grille Pattern Used for Measuring Spatial Resolution.

3. Proposed Technique for Estimating Display Spatial Resolution

This section describes both the initial display calibrations and the proposed display resolution measurement technique. A CCD (charge-coupled device) camera was used for the measurements. Some factors that may affect the selection of a CCD device are briefly described in Appendix A, and additional procedures for use with a device that has not been calibrated are described in Appendix B. The technique described here is similar to that proposed in the VESA

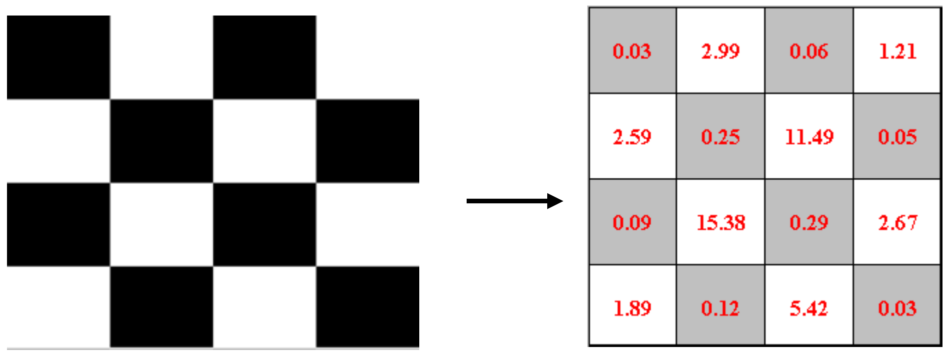
Flat Panel Displays Measurement Standard (VESA, 2001). The VESA standard should be consulted for a more thorough description of the rationale of spatial resolution measurements in general as well as a discussion of related visual display measurements. Each of the visual display test patterns used for the measurements described here are available from DTIC. The test patterns are generated by a Visual Basic program, named Display Test.exe, that will run on personal computers (PC's) with the Microsoft® Windows Operating System.

3.1 Measurement Procedure

3.1.1 Black level, maximum luminance, and luminance fall-off

The *Checkerboards* test pattern, shown in Figure 2(a), consists of black and white squares corresponding to grayscale values of 0 and 255, respectively. Luminance measurements are made at the center of each square. Figure 2(b) shows the results of typical measurements for a rear projection CRT. This measurement will indicate any bright spots and give some indication of the degree to which brightness falls off from the center of the display. Projection CRT displays typically have a bright spot near the center of the image whereas DLP (digital light processing, also known as a digital micromirror device (DMD)) or liquid crystal on silicon (LCOS) projectors, may have a bright spot nearer the bottom of the image. More importantly, when comparing various displays, this test pattern can be used to set similar brightness and constrast levels across each display to be measured.

The black level (i.e., the luminance corresponding to a grayscale value of zero) should generally be set as low as possible. However, the low-luminance and high-luminance output of most displays cannot be adjusted independently, and therefore some compromise must be made between the black level and image contrast. This will depend to some extent on the conditions under which the display will be used. The flight-simulator visual displays that are described here are used in relatively low ambient light conditions, and a relatively low light output is therefore acceptable.



(a) (b)

Figure 2 Checkerboard test pattern used for display adjustment.

3.1.2 Initial display brightness and contrast adjustments

The brightness and contrast of the display should be set such that the overall brightness is at an acceptable level based on the checkerboard pattern **and** there are visible differences between adjacent gray scale levels at each end of the luminance series. The latter condition is tested using the *Contrast Series* test pattern shown in Figure 3. The adjacent patches in the *Contrast Series* can be made to differ by from 5-30 units in grayscale value. For illustration, Figure 3 shows the *Contrast Series* with the largest step size (increments of 30). The actual values chosen will depend on the application. The brightness and contrast settings of the display can generally be found either on the front panel of the display, or for newer displays, in the display settings menu.

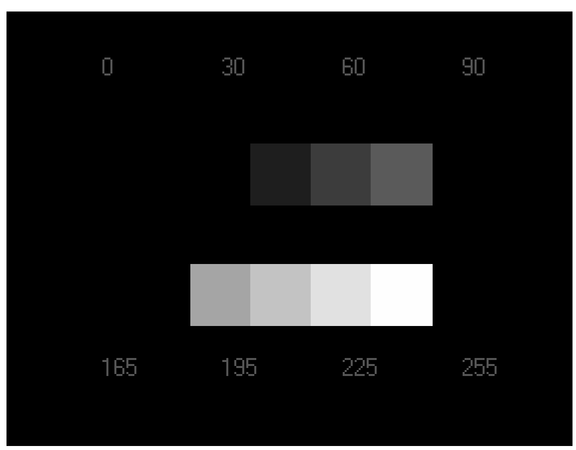


Figure 3 Contrast series test pattern for display adjustment.

3.1.3 Gamma correction and luminance calibration

Display luminance plotted as a function of grayscale value is known as a *gamma function*, an example of which is shown in Figure 4. This function is obtained by sequentially displaying a series of grey scale images corresponding to grayscale values between 0 to 255, and measuring their luminance (using a device calibrated for luminance) near the center of the screen (or elsewhere if desired). [The *Grayscale Series* test pattern increments the display luminance in grayscale steps of 15.] If a power function is fitted to data like those shown in Figure 4, the power exponent is referred to as the gamma value of the display.

The gamma function is often linearized in displays used for perceptual research, usually in order to avoid having the same, or similar, luminance output for two different grayscale values. However, a linear gamma function is inconsistent with both the characteristics of CRT displays and the properties of the human visual system. A CRT display has a gamma near 2.5, which Poynton (1998) attributes to the nonlinear response of the electron gun. Coincidentally, brightness matching experiments with human observers (Stevens, 1960) indicate that the function relating perceived brightness to luminance is a power function with an exponent of about 0.33. The inverse of this exponent is close to the CRT gamma cited by Poynton (1998). Likewise, in CIE (Commission Internationale de l'Eclairage) models, lightness is represented by a cubed root function called L* (Wyszecki & Stiles, 1982). The exponent of this function, 0.333, is also close to the inverse of 2.5. Thus, a gamma function of about 2.5 is a good choice for assuring that adjacent DAC values at both the high and low ends of the luminance scale will appear perceptually different (see earlier discussion of Figure 3).

If the CCD device is uncalibrated, its output should be converted to luminance prior to calculating the Michelson Contrast as described below. This can be accomplished by comparing the CCD output to that of a photometer. This procedure is described in Appendix B.

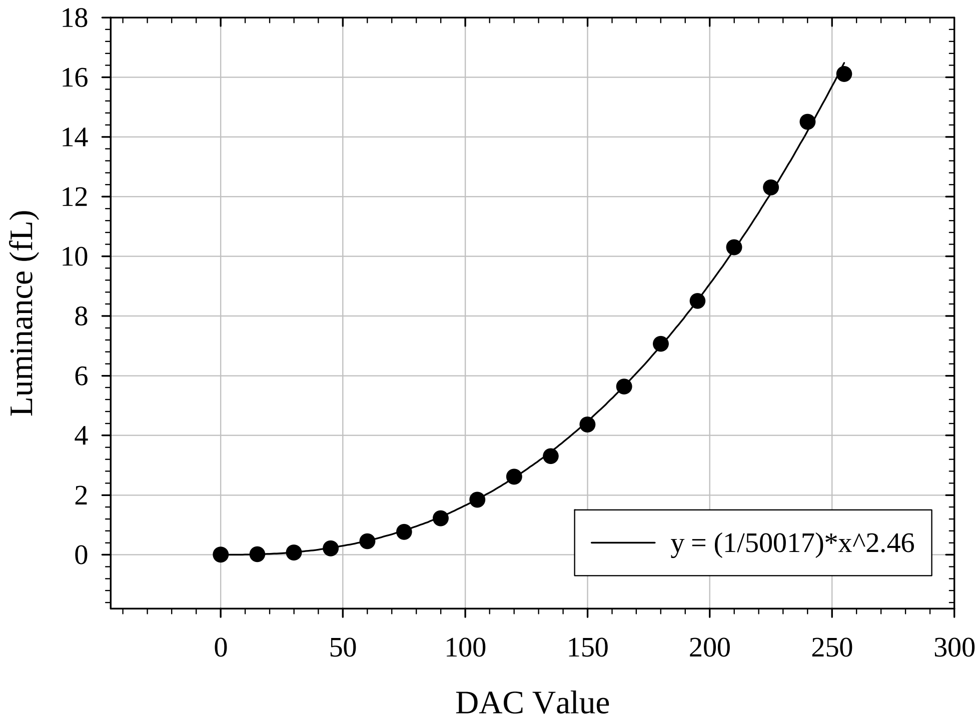


Figure 4 Example gamma function for a CRT display.

3.1.4 Display spatial resolution measurements

The proposed procedure for measuring display spatial resolution is as follows:

a) Display a series of vertical and horizontal grille patterns (Figure 5, left). Vertical grille patterns are used to measure horizontal resolution; horizontal grille patterns are used to measure vertical resolution. For typical displays, grille line widths should range from at least one pixel (1-line-on/1-line-off) to 3 pixels (3-lines-on/3-lines-off). However, for some display systems the contrast of the 1-line-on/1-line-off pattern may be so low that it is not measurable. The *Grille Patterns* feature of the Display Test Program will generate these grille patterns and allow the grille width to be selected. Note that this program will directly address the display pixels and therefore will not be affected by any antialiasing functions that may be available on the videocard (a bitmap or other image that is drawn on the screen while antialiasing is in use may be blurred relative to a non-antialiased image, an important consideration if spatial resolution is being measured).

b) Select a lens and a CCD camera-to-screen distance to provide the required number of CCD samples per cycle of the grille pattern (Appendix A).

c) Capture an image of a portion of each grille pattern with the CCD camera (Figure 5, left) from the desired location on the display. For large projection systems the contrast at the center of the display may be significantly different from that at the edges of the display, therefore it may be desirable to obtain measurements at more than one location on the display.

d) Select several maximum and minimum values from the resulting CCD output (i.e., select the peaks and troughs shown in the right of Figure 5) and find the average maximum value and average minimum value. The luminance plots shown in Figure 5 were obtained by averaging the values of each of the 255 columns of our CCD output (for a vertical grille pattern) and converting each of these 255 values to luminance. This resulted in the periodic pattern shown on the right hand side of Figure 5.

e) Use the average maximum and minimum luminance values for each grille pattern to compute a Michelson Contrast [C_M = (Maximum – Minimum) / (Maximum + Minimum)], for each grille line width. The Michelson Contrast for a typical projection CRT display as grille line width is decreased from 3-lines-on/3-lines-off to 1-line-on/1-line-off, for both horizontal and vertical grille lines is shown in Figure 6.

f) Choose a criterion contrast level, and find the grille line width corresponding to that criterion level. The VESA standard suggests a criterion level of 0.25 for applications involving gray-scale images. This criterion level is indicated by the dashed line in Figure 6.

g) Calculate the spatial resolution of the display system by dividing the number of horizontal (or vertical) pixels by the criterion grille line width. For example, if the criterion vertical grille line width is 1.3 pixels, as shown in Figure 6 left, for a display system with a 1600×1200 pixel format, then the estimated number of resolvable lines would be 1600/1.3 = 1231. This additional conversion provides a simple and easily interpretable way of specifying the spatial resolution of the display system. The screen size and viewing distance can then be used to convert the number of resolved lines to arc-minutes per line pair, or similar measure if desired.

Microsoft® Excel workbooks, named *Luminance Calibration.xls* and *VDE_Workbook.xls*, have been developed for performing the calculations described in sections d) through g) above are available from AFRL. These workbooks are described in Appendix C.

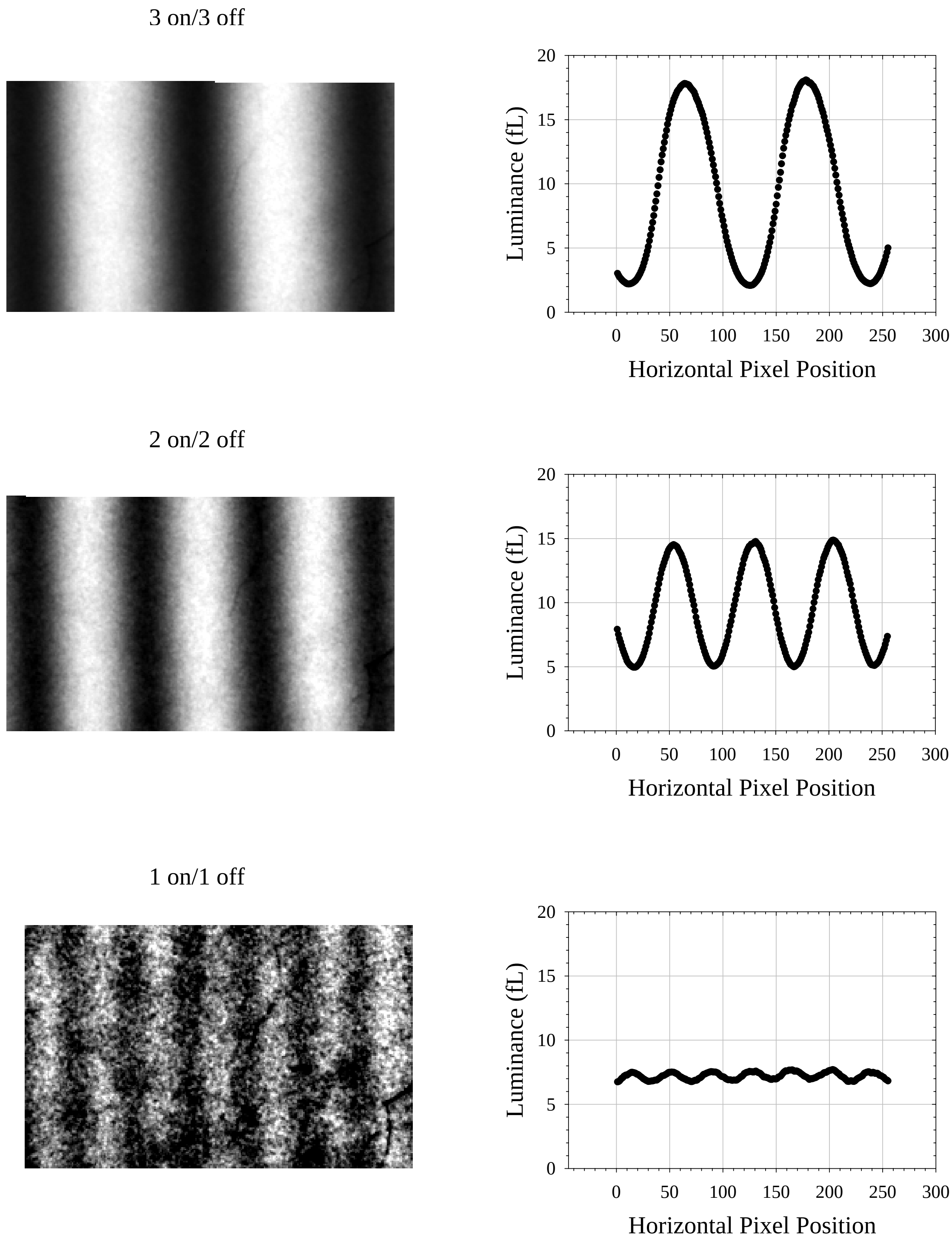


Figure 5 Example grille patterns (left) and luminance measurements (right).

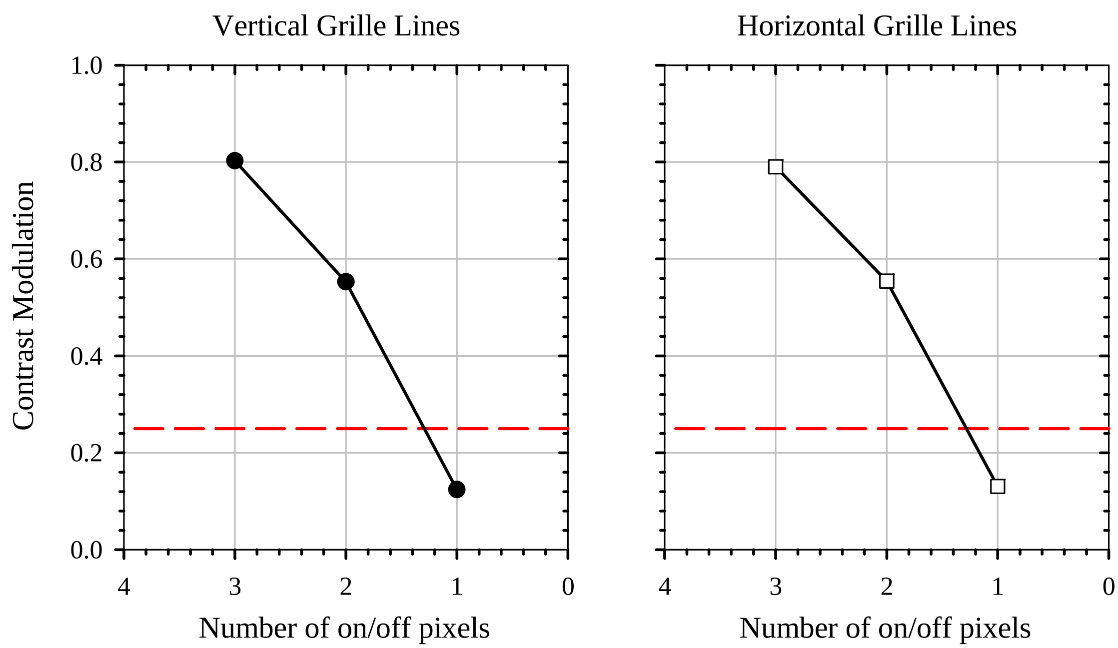


Figure 6 Measured contrast modulation for various grille line widths on a CRT display.

3.2 Typical Spatial-Resolution Measurements

The display measurement technique described above has been used at AFRL, Mesa to characterize a variety of displays, and has proven useful for evaluating displayed image quality. Table 1 provides a summary of some spatial resolution measurements that have been performed on various displays. All measurements were obtained using the SBIG ST7 CCD camera system described in Appendices A and B. The CCD was set to 3 × 3 binning, resulting in a pixel format of 255 × 170 pixels. The distance from the camera to the screen was chosen such that an image area of about 7 mm × 5 mm covered the active area of the CCD. This arrangement assured that at least 20 samples per cycle could be obtained for the 1-line-on / 1-line-off grille pattern at the highest pixel format that was expected to be evaluated (5120 × 4096). The CCD output was converted to luminance by comparing it to luminance measurements obtained with a calibrated Minolta LS-100 photometer (Appendix A). A 25% contrast criterion was used for all spatial-resolution calculations summarized in Table 1.

Display System Spatial Resolution Summary				
Display	**Type**	**Line Rate**	**Resolution (H)**	**Resolution (V)**
Barco 909	CRT	1280x1024	949	884
Barco 909	CRT	1600x1200	1038	836
Barco 909	CRT	2048x1536	907	746
Barco 808s	CRT	1280x1024	983	987
Barco 808s	CRT	1600x1200	997	915
Barco 808s	CRT	2048x1536	913	922
VDC 9500 LC	CRT	1600x1200	1376	1106
VDC 9500 LC	CRT	2048x1536	1407	1137
VDC 8500	CRT	1600x1200	993	875
VDC 8500	CRT	2048x1536	999	881
JVC DLA M15	D-ILA	1280x1024	1424*	N/A
JVC SX-21	D-ILA	1280x1024	4076*	3109*
VDC Sim 1500	LCoS	1280x1024	1992*	1905*
VDC Sim 1500	LCoS	1280x1024	2546*	2191*

* estimated

Table 1 Spatial Resolution Data for Various Displays.

The summary data shown in Table 1 indicate that the spatial resolution of the rear-projection CRTs tested is less than 1500 lines, with typical resolutions of about 1000 lines, regardless of the pixel format chosen. This is due primarily to the limited bandwidth of the CRT components. However, other factors such as age, distance from the projection screen, type of projection optics, screen material, and video cable characteristics also are contributing factors. The Michelson Contrast of a 1-pixel-on / 1-pixel-off grille pattern as displayed on a typical CRT-projector is usually below 25% (as shown in Figure 6). For the digital image light amplifier (D-ILA) and LCoS projectors, however, the effective number of pixels required to obtain 25% contrast is less than 1.0, and so the number of resolved lines obtained using this technique is greater than the pixel format of the display. This result further obviates the necessity of distinguishing between resolution and addressability (i.e, the number of displayed pixels). As noted by Murch and Virgin (1985), for instance, for a given resolution, addressability (or display viewing distance) must be chosen so that the individual pixels are just distinguishable. Thus, a display whose resolution is greater than its addressability (e.g., the digital displays described above) would have to be viewed from a greater distance thus reducing the field of view. Although we have not done so here, this relationship may be quantified using the ratio of the number of resolved lines to the number of addressable lines.

3.3 The Control of Relevant Display System Parameters

Every display system consists of multiple components, and each can potentially affect the spatial resolution of the displayed image as measured by this technique. Thus, there are several variables that must be considered when using this technique.

a) *The image generator (IG)*. The IG and its associated graphics hardware can be extremely complex, and their use typically involves many choices among settings and options that may not be well-defined, and are often interdependent. To the extent that the optimal IG and graphics settings can be determined, this must be done by experienced operators in consultation with the end users who would presumably use the results of the measurement techniques described here.

b) *The mean luminance and color of the displayed image*. With the exception of the D-ILA and LCOS projectors, all measurements described here were made at one mean luminance and color setting, each selected based on the requirements and limitations of the flight simulators used at AFRL, Mesa. The D-ILA and LCOS projectors have substantially higher light output compared to the CRT projectors and in some cases could not be adjusted to match the mean luminance level typical of the CRT projectors. Luminance levels were verified using the checkerboard pattern described in Section 3.1.1.

c) *The pixel format*. As is shown in the data of Table 1, increasing pixel format does not necessarily increase the spatial resolution of CRT displays. It would presumably do so if the bandwidth of the CRT were sufficiently high. However, in that case, the individual pixels would be visibly separated at lower line rates, which might produce other perceptual problems. Further, an additional specification would be needed in that case, since the spatial resolution as specified by the technique described would be the same for the two pixel formats. This latter issue has been discussed elsewhere (Murch & Beaton, 1988), and should be considered when determining the most appropriate way to specify spatial resolution in a paricular application.

d) *The projector*. The projector itself is a multi-component system whose components (e.g., electronics, phosphers, projection optics) properties may effect the spatial resolution of the system. Only the adjustment of brightness and contrast has been discussed here. However, there are a multitude of other display settings that may affect resolution, such as convergence, stigmatism, and RGB gain settings. Also, in the case of digital projectors in particular, the pixel format of the IG graphics card should be chosen to match the native pixel format of the display.

e) *The projection screen*. High-quality rear-projection screens do not significantly affect the spatial resolution of even the highest resolution projectors currently available. Screen properties may, however, affect the relative quality of the center and edge of large projected images. These screen properties may also accentuate, or even interact with, the decrease in image quality associated with light projected off the primary axis of the projector optics.

3.4 Limitations of the Proposed Technique

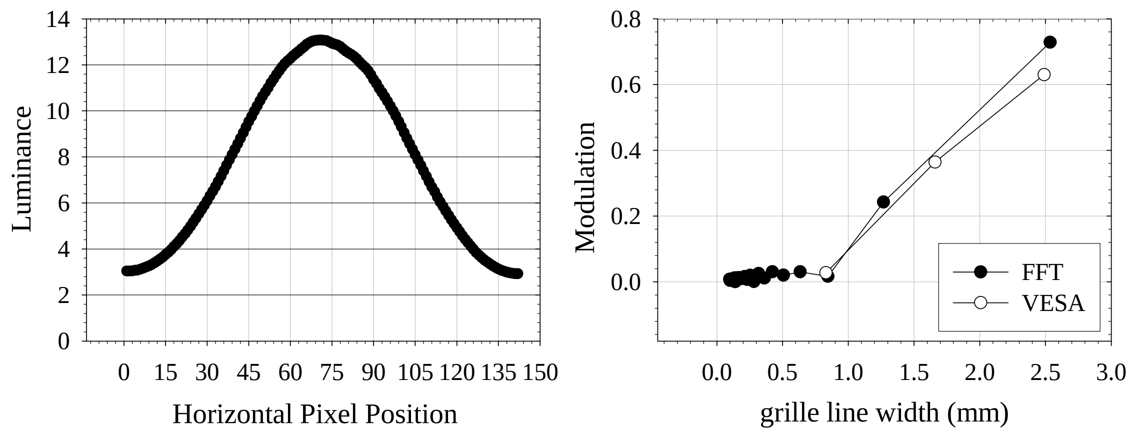
The grille-pattern test stimuli described here are inherently simple and are perhaps the most fundamental stimuli that can be used to assess the spatial resolution of pixellated imagery. However, the resolution estimates obtained with these stimuli may not correlate with performance on tasks that are less dependent on spatial detail. Furthermore, the spatial properties of most flight-simulator visual imagery are not the same at all locations within the image. Therefore, there is no single resolution measure that adequatly characterize the entire image. It is important to recognize this problem even though it cannot be easily resolved in most applications.

As discussed earlier, in order to meaningfully interpret the results of the technique described here (or any comparable technique), it is necessary that all displays under evaluation be similarly calibrated (see section 3.1).

The present technique does not take into consideration the possible effects of glare from ambient light, or the effects of veiling glare. The technique was developed for evaluation of displays used for simulation which have a relatively low maximum luminance. For significantly brighter displays, where veiling glare may be more of an issue, the VESA Flat Panel Display Measurements Standard describes two techniques to reduce its effect. The use of a lens with a wider field of view than that used in the present application may also increase veiling glare.

3.5 Modulation Transfer Function (MTF) Analysis

A line spread function (LSF) is the distribution of light associated with a luminous line, such as one of the "on" half-cycles of the square wave of Figure 1. An actual LSF of one "on" grille line, measured from a CRT projector, is shown in Figure 7(a). The MTF of this LSF was obtained by performing a Fast Fourier Transform (FFT) on the latter (using SigmaPlot 8.0). The real and imaginary components of the FFT were squared and summed. The square root of this result was then taken to obtain the magnitude. The computed magnitudes were also scaled relative to the total power of the FFT. In order to relate the FFT magnitude to the measured modulation obtained for each grille pattern using the VESA standard, the effective spatial frequency of the grille patterns had to be converted to comparable units (mm) by taking into account both the number of pixels and the field of view of the CCD camera. Both the FFT results and the results of a measurement obtained using the VESA standard are shown in Figure 7(b). The two curves are very similar, however, the proposed technique is clearly simpler to describe, easier to interpret, and does not require the use of specialized analysis software.



(a) (b)

Figure 7 Two methods for assessing spatial resolution.

4. Conclusions

The measurement technique described here provides a straightforward and intuitive method for evaluating visual display spatial resolution. It provides easily interpretable results, as shown in Table 1, that can be used to compare various display types. Furthermore, this technique provides results that can be easily communicated to a variety of end users, even those that may have limited technical experience. Application of this technique clearly shows that a distinction must be made between pixel format and resolution. A specific example of why this distinction is important in practical applications is also given by Geri (2001).

A display capable of receiving a very high frequency input cannot necessarily reproduce those high frequencies in the output image. For this reason, performance on visual tasks, such as those that may be conducted in a flight simulator, may depend on display resolution rather than pixel format. This was found to be the case for an aircraft aspect-angle recognition task performed in a flight simulator configured with a CRT display (Winterbottom, Geri, & Pierce, 2003). That study established a direct relationship between a physical measure of visual display spatial resolution and human visual performance, and thus further confirms the importance of spatial resolution in evaluating and characterizing the properties of visual displays.

5. REFERENCES

Geri, G.A. (2001). Measuring display resolution using a VESA standard. *Journal of the SID*, **9**, 337-338.

Ginsburg, A. P. (1986). Spatial filtering and visual form perception. In Boff, K. (Ed.), *Handbook of Perception and Human Performance*, Vol 2. (pp. 34-41). New York: John Wiley & Sons.

Kelly, G. (1992). Measurement of modulation transfer functions of simulator displays. Technical Paper No. AL-TP-1992-0056. Human Resources Directorate Aircrew Training Research Division, Williams Air Force Base, AZ.

Merriam-Webster, Inc. (2003). *Merriam-Webster's collegiate dictionary*. 11th ed. Springfield, MA: Merriam-Webster, Inc.

Murch, G.M. & Beaton, R.J. (1988). Matching display resolution and addressability to human visual capacity. *Displays*, January, 23-26.

Murch, G.M. & Virgin, L. (1985). Resolution and addressability: How much is enough? *SID 85 Digest*, 101-103.

Poynton, C. (1998). The rehabilitation of gamma. In Rogowitz ,B. E., and T. N. Pappas (Eds.), *Human Vision and Electronic Imaging III*, Proceedings of SPIE 3299, (pp.232-249). Bellingham, WA: SPIE.

Rubin, M.L. & Walls, G.L. (1969). *Fundamentals of Visual Science*. Springfield, IL: Charles C. Thomas.

Stevens, S. S. (1960). The psychophysics of sensory function. *American Scientist*, **48**, 226-253.

Video Electronics Standards Association. (2001). *Flat Panel Display Measurements Standard*, Version 2.0. Milpitas, CA: VESA.

Winterbottom, M., Geri, G. A., & Pierce, B.J. (2003). Effect of display line rate and antialiasing on the recognition of aircraft aspect angle. In *Society for Information Display 2003 International Symposium: Digest of Technical Papers*, **34**, (pp.288-291). Baltimore, MD: SID.

Wyszecki, G. and Stiles, W. S. 1982. *Color Science: Concepts and Methods, Quantitative Data and Formulae*, 2nd Ed., New York: Wiley.

6. APPENDIX A

SELECTING A CCD CAMERA AND LENS

The CCD device used at ARFL was an SBIG ST7 imaging camera equipped with a Kodak KAF-0401 CCD. Several characteristics that should be considered when selecting a CCD device for making spatial-resolution measurements are described below.

6.1 Number of Pixels

The number of usable pixels is the single most important characteristic that must be considered in the present context. Video cameras that are required to output pixel values at high rates (typically 30 Hz or more) tend to incorporate smaller CCDs. Single frame devices, on the other hand, do not have this temporal constraint and so tend to provide more pixels. Single frame CCD cameras generally acquire and transmit images more slowly but are generally more accurate, and allow direct control of more aspects of their operation. The SBIG ST7 CCD camera is a single-frame device and has a maximum pixel format of 765 × 510. The number of pixels will affect the distance and field of view required for measurement.

6.2 Field of view

For spatial resolution measurements like those described in the VESA Flat Panel Displays Measurement Standard, and discussed here, a narrow field of view is desired. A minimum of approximately 20 samples per cycle (10 samples per grille line) was chosen for these measurements. In order to choose an appropriate lens for the CCD camera, the maximum pixel format of the display to be evaluated (in this case, approximentely 5000 × 4000 pixels), the required displayed image size (52 × 43 inches or 1321 ×1052 mm)), and the choice to use the lowest CCD pixel format (i.e., 255 × 170 pixels with 3 × 3 binning) were all considered. These parameters resulted in a required image measurement area of approximately 7 mm in the horizontal dimension [255 pixels /10 pixels/line = 25.5; (1321 mm/5000 lines) × 25.5 = 6.7mm]. A C-mount Navitar 6x zoom lens was found to provide the necessary field-of-view. A beamsplitter and viewing reticle were also used with the lens in order to simplify the focusing procedure, which would otherwise be very time consuming with this single frame camera.

6.3 Binning

As noted earlier, the SBIG ST7 has a maximum pixel format of 765 × 510 pixels. Many CCD cameras have a binning mode which effectively sums adjacent CCD pixels thus reducing the effective number of pixels. For example, the SBIG ST7 has 2 × 2, and 3 × 3 binning modes, which reduce the effective pixel format to 382 × 255 and 255 × 170, respectively. Note also that the sensitivity of each binned pixel will increase due to the pooling of response of each of the physically separate CCD pixels within the binned pixel. For example, the response of a 3x3 binned pixel will be approximately 9 times greater because it is summing the response of 9 individual CCD pixels.

7. APPENDIX B

CCD-CAMERA CALIBRATION

We describe here several issues relevant to the calibration of the SBIG ST7 CCD camera used for the spatial-resolution measurements.

7.1 Conversion of CCD Output to Luminance

The calibration of light-measuring devices is inherently difficult, and this is particularly true for more complex devices such as those based on CCD technology. As a practical matter, it is sound practice to verify calibration whenever possible, preferably using a relatively simple and inexpensive photometer whose calibration can be more easily maintained. A Minolta LS-100 photometer was choosen for this purpose.

Figure 8 shows a series of CCD values compared to corresponding luminance values determined by the calibrated Minolta LS-100. Fitting a power function (the same procedure used for measuring display gamma described in section 3.1.3) allows a conversion factor between CCD value and luminance to be established (for the particular lens and camera settings used). Different CCD devices may be capable of different ranges of output. For example, the SBIG ST7 used here is a 16 bit device, therefore its output can range from 0 to 65536. A 12 bit device will output values ranging from 0 to 4096. This may affect the accuracy, or granularity, with which luminance can be measured with the CCD device.

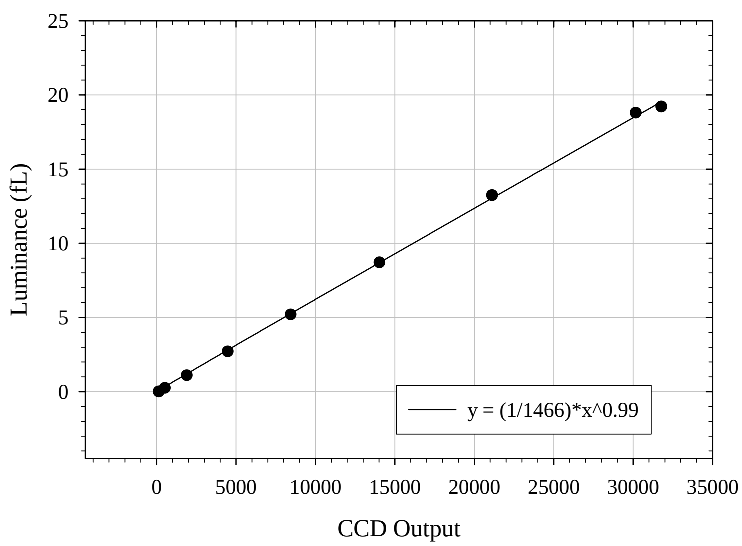


Figure 8 Conversion of CCD output to luminance values.

7.2 Exposure duration and binning

Because the *f*-stop setting of the CCD camera lens may affect spatial resolution measurements, it is preferable to keep it constant and adjust the camera response by varying the CCD exposure duration. In order to do this properly, however, it is necessary to determine how the CCD output varies with exposure duration for a constant light stimulus. These data are shown in Fig. 9. Ideally, CCD output would be directly proportional to exposure duration. The data of Fig. 9 indicate that this proportionality is only approximate. As a result, when using this device, the necessary corrections must be made if exposure duration is changed during a measurement series.

Because CCD binning is performed by summing adjacent CCD pixels, it also has a significant effect on CCD output (Figure 10). CCD output is also more likely to be saturated. Shown in Figure 11 is a comparison of CCD output for 1 × 1 binning and 3 × 3 binning. Note that the CCD response for 3 x 3 binning, shown by the ratio in Figure 10, is roughly 9 times that of 1 x 1 binning.

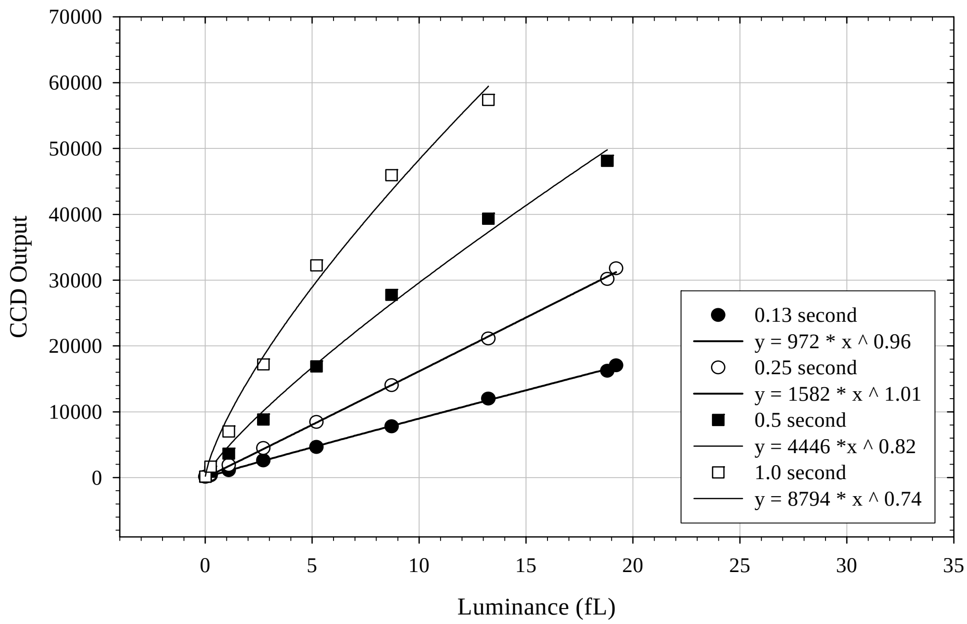


Figure 9 Effect of luminance and exposure duration on CCD output.

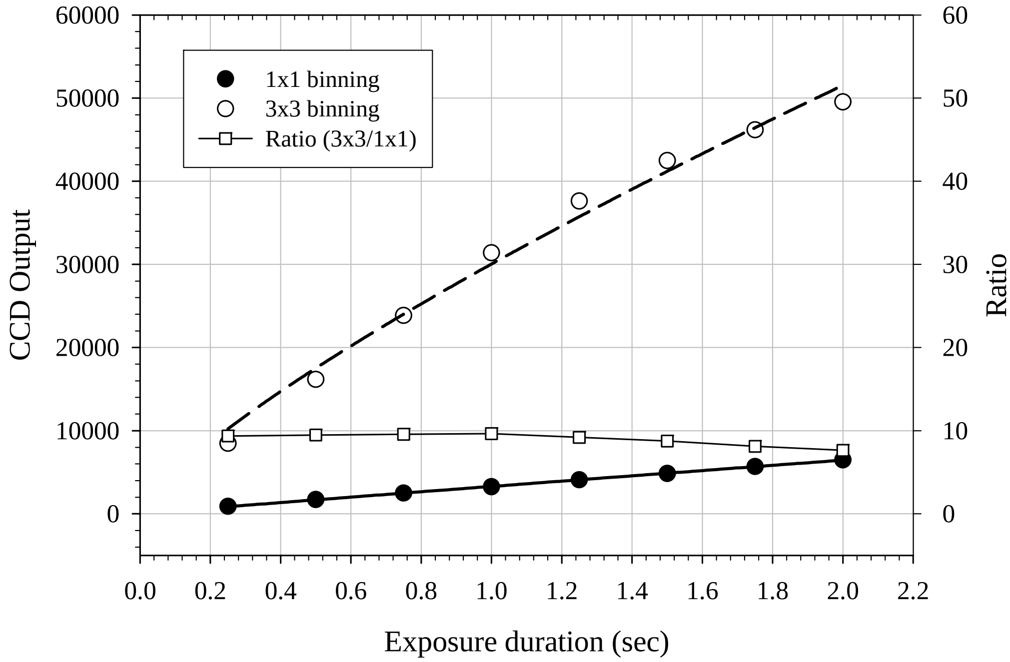


Figure 10 Effect of CCD binning and exposure duration on CCD output.

7.3 Flat-field correction

Since CCD values may be taken for measurement purposes across the entire CCD array it should be verified that CCD output does not depend significantly on pixel position (i.e., CCD values at the center of the array do not differ significantly from those at the edge of the array). This could be caused by either the lens or the CCD array. To verify that the CCD values did not vary significantly across the CCD array for the SBIG ST7 and the Navitar 6x lens, an integrating sphere (Hoffman Engineering, Model LS-65-6S (see note in Appendix F Equipment Used)) was used that produced a nearly equiluminant field. As shown in Fig 11, CCD pixel output is nearly identical across one row of the CCD array. This indicates that CCD sensitivity does not change significantly across the CCD surface and that the lens does not cause differential distortion. However, a lens with a larger field-of-view than the Navitar 6× is likely to cause some distortion in the distribution of light on the CCD array. If the distortion is known for a given CCD and lens a correction factor could be used prior to any subsequent calculations. A significant amount of effort goes into the flat field correction for CCD devices that have been calibrated for luminance because the correction factor may change for each lens, *f*-stop setting, and focal length that may be used.

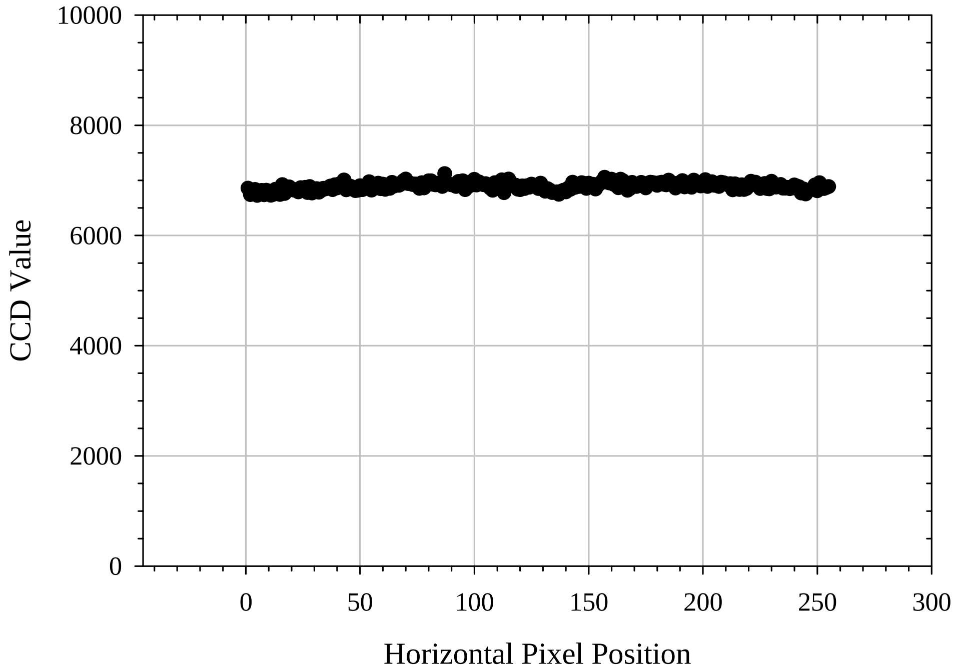


Figure 11 CCD calibration with an integrating sphere.

If an integrating sphere is not available, a measurement of nearly any illuminated surface could be obtained with the CCD device and then compared to measurements taken with a photometer. Plotting luminance measurements from the same locations along the surface for both the CCD device and the photometer will indicate if there is significant variation in the CCD output. When comparing CCD output with values from a calibrated comparison device with a measurement field that is small compared to the displayed image, care should be taken with the positioning of each device. Depending on the type of lens used with the CCD camera, it may be capable of measuring a substantially larger area than the calibration comparison device. If this is the case, the comparison device should be rotated rather than translated when measurements are made across the displayed image. This is particularly important when measurements are made on surfaces that may have direction-dependent properties (for example rear-projection screens).

7.4 Photopic Correction

The response of a CCD camera to light may be significantly different from that of the human eye. Figure 13 shows how the KAF-0401 CCD response to light differs from that of the photopic luminosity function. Some commercially available CCD cameras include a light filter that transforms the response of the CCD camera to nearly that of the photopic luminosity function. If a corrective filter is not supplied, custom filters can be obtained, although they are expensive in small quantities and they may be difficult to mount depending on the configuration of the CCD camera. A photopic correction is not necessary in all applications.

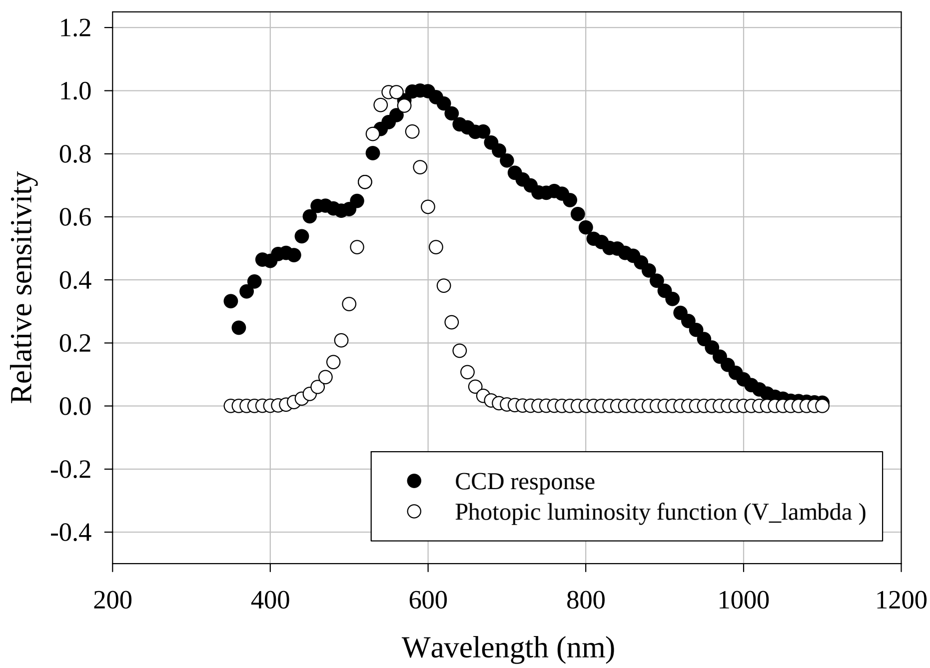


Figure 12 Comparison of CCD response and the CIE photopic luminosity function.

7.5 Measurement consistency

While there is no reason to expect significant differences in successive measurements with the same CCD camera settings, it is worthwhile to verify that the CCD output does not vary significantly over time. Figure 8 shows CCD measurements of the same Photo Research reference light (stable light souce) on two successive days. There is some pixel to pixel variation in output, however the best-fit line to the the data from the two days has a slope close to 1.0, indicating that the two measurments are nearly identical. The average difference is approximately 2.5%. The output of a CCD camera can also vary with temperature. This can be minimized by subtracting a dark image measurement from each light measurement. This option should be used if it is available with the CCD camera. Some cameras may also be equipped with a cooling fan. This is a desirable feature if very low luminance levels need to be measured. The portion of the procedure described in Section 7.1 is performed by the Luminance Calibration Workbook.

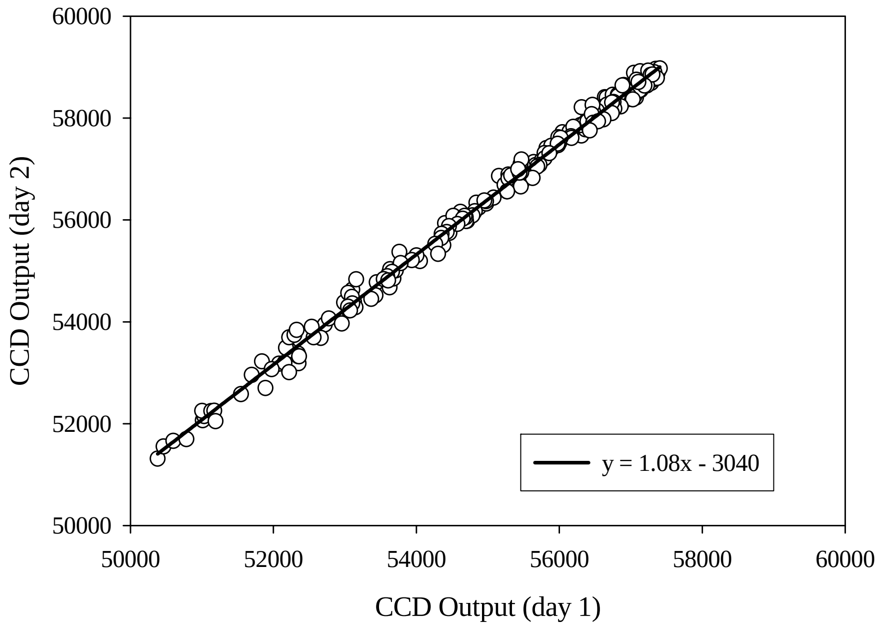


Figure 13 CCD pixel values measured for on two successive days.

8. APPENDIX C

DATA ANALYSIS WORKSHEETS IN MICROSOFT® EXCEL

Several Microsoft® Excel workbooks have been developed to simplify the analysis of the CCD data and are available through DTIC. These workbooks are used for luminance calibration and to estimate spatial resolution as described in Sections 3.1.3 and 3.1.4. The functions of the various worksheets and, the macros that simplify the entry of some of the values in these worksheets are described here. Additional instructions can be found in each worksheet. Microsoft® Excel worksheets are currently limited to 255 columns, and so Microsoft® Excel workbooks were designed to analyze a CCD-output array of only 255 × 170 pixels. However, the general procedure could be extended to any size array if a program is available which can process arrays larger than 255 columns (Matlab or SigmaPlot, for example). Furthermore, the worksheet labeled *Resolved Lines* can be used seperately as a display evaluation summary page for any CCD device once Michelson Contrast has been calculated for each grille line pattern. The procedure for calculating the number of resolved lines using these worksheets is described below.

8.1 Luminance Calibration (LC) Workbook

The LC workbook is used to calibrate the light measurement device (in this case a CCD camera), if necessary (see also Section 3.1.3 and Appendix B). The CCD measurements made on the homogeneous fields, corresponding to various graylevels (0-255 in steps of 30), are imported into the appropriate worksheet in the Microsoft® Excel workbook, *Luminance Calibration.xls*. The CCD measurement array must be entered into each worksheet beginning at column 1 / row 2. The first row of each worksheet contains a formula that will compute the average of the entire measurement array. For this technique the luminance measurements were measured in grayscale increments of 30, with the addition of a measurement at 255. If more or fewer measurements are desired, worksheets may be added or deleted as required.

The last worksheet in the LC workbook is labled *Summary*, and contains a column, labeled *CCD*, whose entries are the averages of the CCD-array data from each graylevel worksheet. These entries are calculated automatically as the CCD-array data are imported into the corresponding worksheets. Luminance values obtained for each grayscale level using a calibrated photometer must be entered in the column labeled, *Photometer*. The *Summary* worksheet also displays a graph of the measured luminance values plotted as a function of the average CCD values. The graph includes an automatic power function fit (Microsoft® Excel trend line) to the plotted data. The fitted power function is used to convert the uncalibrated CCD data to calibrated luminance. {Note that Microsoft® Excel often does not provide a good curve fit, and therefore it is suggested that another program (e.g., SigmaPlot) be used for this purpose. If this option is not available, removing the data corresponding to the zero gray level often result in a better fit.} The values resulting from the curve fitting are used in a subsequent calculation described below.

8.2 Visual Display Evaluation (VDE) Workbook

The VDE workbook is designed to find the average maximum and minimum CCD-array values from the grille pattern measurements, convert the values to luminance based on the curve-fitting results from the LC Workbook, calculate the Michelson Contrast for each grille pattern, and estimate the spatial resolution of the display in terms of number of resolved lines (see Section 3.1.4). The function of this workbook is described below. The worksheet labeled *Instructions* also summarizes the steps required to use the VDE Workbook.

Worksheets 2-9 in the VDE workbook are used to find the average minimum and maximum values for each grille pattern. This is done by inserting the CCD-array measurements for each grille pattern (previously saved as text files) into the appropriate worksheet (i.e., insert the 255 × 170 array for a 1-on/1-off vertical grille measurement into the worksheet labeled *1-1v*, etc.). As each 255 × 170 array is inserted, the columns will be automatically averaged for the worksheets containing the vertical grille-pattern data, and the rows will be automatically averaged for the worksheets containing the horizontal grille-pattern data. For the vertical grille-pattern data, the average of each worksheet column is shown below the data. For the horizontal grille-pattern data, the average of each worksheet row is shown to the right of the data. In addition, the averaged data is automatically displayed in a plot located near the top of each worksheet.

The first step in estimating Michelson Contrast is to determine the CCD values corresponding to the peaks and troughs of the averaged data for each grille pattern.. This is accomplished using two Visual Basic macros that can be run by selecting “Tools – Macro – Macros” in the Microsoft® Excel toolbar. The macros are named *findhilohoriz* or *findhilovert* and are used for the horizontal and vertical grille measurements, respectively. The number of peaks and troughs identified by the macros depends on the number of grille lines measured. These values are placed in a two-column table located under the CCD values. The “Max” and “Min” values should be compared to the graph to verify that they are accurate and that there are an equal number of “Max” and “Min” values for the computation of Michelson Contrasts. The macros generally work well for smooth data. However, lower contrast data, such as from the 1-on/1-off grille patterns at high pixel formats, may be more noisy, and the macros may not accurately select the miniumum and maximum values. In this case, these values can be selected manually by pointing the mouse at the estimated maximum and minimum points on the plotted graph. Microsoft® Excel will display the x and y values for the selected data points, which can then be typed into the appropriate cell in the “Max”-“Min” table.

The worksheet labeled *Contrasts-Uncorr* consists of nine tables whose entries are calculated automatically after the macros described above are run. Eight of the tables show the “Max”-“Min” data from each of the eight grille-pattern worksheets, the Michelson Contrasts calculated from the data in each row of the table, and the mean Michelson Contrast. The ninth table is a summary of the mean Michelson Contrasts from the other eight tables. It is necessary to delete the contents of cells containing “Max” and “Min” values of zero, and the associated cell that calculates the Michelson Contrast. Values of zero occur when the number of grille lines, as measured, is less than the number of rows in the table.

The worksheet labeled *Contrasts-LCorr* converts the CCD values from the *Contrasts-Uncorr* worksheet into luminance values, and calculates the corresponding Michelson Contrast. It may again be necessary to delete the contents of the worksheet cells containing “Max” and “Min” values of zero, and the associated cell that calculates the Michelson Contrast. The luminance correction is achieved by entering the appropriate values into the cells labeled “A” and “B” at the top of the worksheet. These values were derived from fitting a power function of the form $y = A \cdot x^B$ in the LC workbook described in Section 8.1.

The worksheet named *Resolved Lines* takes the Michelson Contrasts computed in the “SpRes-LCorr” worksheet and plots them against grille line width (delete cells in the summary table for grille line widths that were not measured). When the pixel format of the displayed image is entered, the number of resolved lines is calculated by estimating the grille-line width at which a horizontal line, corresponding to the chosen threshold criterion level of contrast, intersects one of the lines connecting the plotted data points. Note that if the 25% level is below the measured contrast for the 1-on/1-off grille line, the grille-line width at threshold is determined by the intersection of the criterion line with an extension of the line connecting the 2-on/2-off and 1-on/1-off data points (i.e., not with the line connecting the 1-on/1-off data point with the origin of the graph). When this situation arises, the word “Extrapolated” appears in the cell adjacent to the calculated value. Due to a limitation on the number of logic statements permitted for one cell in Microsoft® Excel spreadsheets, errors will sometimes occur in this calculation. The calculations described above should therefore be verified by comparing the value of the cell labeled “Line Width at Criterion Level” with a visual estimate of the criterion line width from the plotted data..

The horizontal and vertical resolution in terms of number of resolved lines is also shown in the worksheet, and the resolution in terms of arc minutes per line pair will also be calculated if the dimensions of the display area and the viewing distance are entered at the bottom of the worksheet. This worksheet provides a concise summary of the spatial resolution measurements and can be used without the previous worksheets if a CCD device that has already been calibrated for luminance (or for a CCD device with a different pixel format is used) by simply entering the Michelson Contrasts into the appropriate cells in the summary table.

The final worksheet is labeled *Lum & Contrast.* This page provides estimates of the luminance fall-off across the display, average luminance, average contrast, etc., based on the measurments using the checkerboard pattern. These values can be obtained by entering each measurement taken using the checkerboard pattern into the corresponding diagram in the worksheet. The bottom of the worksheet provides a location to enter the brightness/contrast settings of the display for future reference.

9. APPENDIX D

ACRONYMS AND DEFINITIONS

CCD- charge-coupled device

CIE- Commission Internationale de l'Eclairage (color standard which includes the following color spaces: CIE Lab, CIE L*a*b*, CIE Luv, and CIE xyz)

CDROM- compact dDisk - read only memory

CRT- cathode ray tube

DAC- digital to analog convertor

D-ILA- digital image light amplifier

DLP- digital light processing

DMD- digital micromirror device

FFT- fast fourier transform

Hz- Hertz

IG- image generator

LCoS- liquid crystal on silicon

LSF- line Sspread function

mm- millimeter

MTF- modulation transfer function

PC- personal computer

RGB- red, green blue

VESA- Video Electronics Standards Association

10. APPENDIX E
FILES ON CDROM

Display Test.exe - Display Calibration Program

Luminance/Contrast: Checkerboards, Contrast Series, Grayscale Series (Gamma) Spatial Resolution: Grille Patterns

VDE_Workbook.xls - Visual Display Evaluation

Worksheets: Instructions, 1-1v, 2-2v, 3-3v, 4-4v, 1-1h, 2-2h, 3-3h, 4-4h, (Worksheets 2-9 referenced on page 34), Contrast-Uncorr, Contrasts-LCorr, Resolved Lines, Lum&Contrast

Luminance Calibration Workbook.xls

Worksheets: 0, 30, 60, 90, 120, 150, 180, 210, 240, 255; summary

11. APPENDIX F

EQUIPMENT USED

Photometer
http://ph.konicaminolta.com.hk/eng/industrial/light.htm
Minolta LS-100
Luminance Meter LS-100 is compact, lightweight meter for measuring the luminance of light sources or reflective surfaces. The SLR (Single-lens-reflex) optical system allows precise aiming and ensures that the viewfinder shows the exact area to be measured. Acceptance angles of only 1° for LS-100 allow accurate measurements of small specimen areas.

CCD
http://www.kodak.com/global/en/digital/ccd/products/fullframe/KAF-0402E/specifications.jhtml?id=0.1.4.6.4.7.4&lc=en
Kodak KAF 401

- 393K Pixel Area CCD
- 768H x 512V (9 µm) Pixels
- Transparent Gate True Two Phase Technology (Enhanced Spectral Response)
- 6.91 mm H x 4.6 mm V Photosensitive Area
- 2-Phase Register Clocking
- 70% Fill Factor
- Antiblooming Protection
- Low Dark Current (<7pA/cm2 @ 25oC)

Lens
www.navitar.com

Camera
www.sbig.com
Santa Barbara Instrument Group Model ST-7

Integrating Sphere
www.sphereoptics.com
March 31, 2003 - Hoffman Engineering Corporation, Stamford, CT is now SphereOptics Hoffman, LLC located in central New Hampshire.
SphereOptics assumes responsibility for the manufacture, marketing, and sales of the precision radiometric and photometric integrating sphere product line previously offered by Hoffman Engineering.

Photo Research, Inc
www.photoresearch.com
9731 Topanga Canyon Place
Chatsworth, CA 91311-4135

SigmaPlot 8.0

www.spss.com
SigmaPlot graphing software from SPSS Inc (Statistical Package for the Social Sciences). SigmaPlot offers seamless Microsoft® Office integration, to easily access data from Microsoft® Excel spreadsheets and present results in Microsoft® PowerPoint® presentations.

MATLAB® Excel Builder
http://www.mathworks.com
Enables you to easily convert complex MATLAB algorithms into independent Excel add-ins. Take advantage of the flexible, matrix-based MATLAB programming environment, with thousands of available math and graphics functions, to quickly prototype and develop computationally intensive models.

Microsoft® Excel
www.microsoft.com